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Learning by Doing with Shareable Interfaces

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Abstract

New technologies, such as multi-touch tables, increasingly provide shareable interfaces where multiple people can simultaneously interact, enabling co-located groups to collaborate more flexibly than using single personal computers. Soon, these technologies will make their way into the classroom. However, little is known about what kinds of learning activities they will effectively support that other technologies, such as mobile devices, whiteboards, and personal computers, are currently unable to do. We suggest that one of the most promising uses of shareable interfaces is to support learning through exploration and creation. We present our work on DigiTile as a case study of how shareable interfaces can enable these forms of learning by doing. We demonstrate how DigiTile supports collaboration, present a field study on its learning benefits, and show how it can fit into a larger computing ecology.

Keywords: [shareable interfaces](#), [multi-touch tables](#), [learning by doing](#), [collaborative learning](#), [constructionism](#)

Vision and Background

Personal computers (PCs) are becoming commonplace in school and leisure settings. How to incorporate them effectively in modern education curricula is now a central attainment target (Littleton and Light 1999). A new generation of technologies is about to make its way into the classroom. Many of these are designed to provide shareable interfaces, where multiple users can interact simultaneously. For instance, SMART Technologies is planning to market multi-touch tables for classroom use in 2009. How can these technologies be put to good pedagogical use? In particular, what kinds of classroom learning activities will they support and how will they compare with other technologies, such as mobile devices and PCs?

Since early research can often affect how a technology is understood and utilized (Bijker 1995), it is timely for developers, educators, and researchers to come together to determine how this new technology can benefit learning. In this article, we present our vision of shareable interfaces supporting learning by doing, using our work on DigiTile as a case study.

Learning by Doing

A core challenge for constructivist educators is designing environments that enable learning by doing, where learners actively engage with a domain through exploration and creation (Bruner 1966). One approach is to provide inquiry tools; learners can actively explore the domain concepts themselves, rather than being told about them. In *constructionism*, learners create personally meaningful public artifacts with tools that allow them to engage important ideas (Papert 1991). Because the artifacts are personally meaningful, learners are able to forge meaningful connections with the ideas underlying them. This emphasis on environments and tools, rather than on subject matter and lesson plans, can be traced back to Montessori's prepared environment and Fröbel's manipulatives (Standing 1957). The computer can be a powerful tool for creating these systems (Kay and Goldberg 1977; Rick and Lamberty 2005).

However, it can be difficult to actively engage students in this manner in whole classroom settings, especially given current teacher-to-student ratios. In contrast, collaborative work in small groups allows students to actively work with each other (Cohen 1994; Webb and Palincsar 1996). Moreover, there is growing recognition that computers can be used to support collaborative learning (Scardamalia and Bereiter 1991; Dillenbourg 1999). The development of educational software to support co-located collaboration, however, has until now been constrained by the available single-user technology (e.g., PDAs, PCs). Shareable interfaces offer much potential for new possibilities, enabling students to work together more actively for a number of domains. For example, they allow co-located students to construct digital content together that are coupled with other learning activities, such as math. This form of co-construction allows learners to share, discuss, and reflect upon their own and each others' ideas.

Shareable Interfaces

There are essentially two forms of shareable interfaces: distributed systems and single display groupware. In *distributed systems*, multiple components are used in tandem to create a distributed interface to a single system. While any particular component may only support a single user, the integration of the components makes the interface shareable. Because of their distributed nature, these systems can often adapt to large groups, including whole-class work. Technologies that support distributed systems include mobile devices and PCs. *Single display groupware*, on the other hand, support multiple users interacting simultaneously at the same display (Stewart, Bederson, and Druin 1999). Since the displays are limited in size, these systems tend to support small groups (i.e., two to four learners), typically working together on the same task. Technologies that support single groupware include whiteboards and tabletops.

In the Ambient Wood project, groups of 10- to 12-year-olds used a variety of shared technologies to discover more about invisible ecological processes while exploring a physical woodland (Rogers et al. 2004b). These included mobile devices and shared displays that were customized to support the learning activity of scientific inquiry. In RoomQuake (Moher 2006), the classroom itself essentially became a shareable interface through a combination of Pocket PCs strategically placed throughout the classroom at stations. Throughout a normal school day, seismic events were programmed to randomly occur to make the simulation more authentic. When they occurred, the whole class broke up into small groups to record dynamic readings of the simulated earthquakes. The recorded readings were then used to create a physical model of the earthquake; string and Styrofoam balls were hung from the classroom ceiling to physically show the epicenter of the digitally recorded earthquakes. In a follow-up project, WallCology (Moher et al. 2008), wall displays were designed to simulate windows as part of the classroom wall, with simulated life forms living beneath. Classrooms of children collaborated to track the creatures and understand what conditions allowed them to prosper.

Early work on single groupware focused on using multiple computer mice or pens as input to traditional desktop PCs. Learning applications that were developed included collaborative storytelling (Benford et al. 2000) and learning about prime numbers (Scott, Mandryk, and Inkpen 2002). This early work demonstrated how working simultaneously could be more enjoyable and effective than taking turns (Inkpen et al. 1999). A more recent input development for single display groupware is *tangible interaction*, where users physically manipulate tangible artifacts to interact with digital content. Learning applications developed for this approach include reading (Sluis et al. 2004), rhetorical skills (Stringer et al. 2004), programming (Gallardo, Julià, and Jordà 2008), and dynamic systems (Zuckerman, Arida, and Resnick 2005).

One of the most promising technologies to support single display groupware is the *multi-touch table*, a horizontal display that can detect multiple concurrent touches. Because the display is also the touch interface, users can manipulate the object directly, creating a more appealing and natural means of input (Shen, Everitt, and Ryall 2003). Groups can “dive in” to a task, since communication, such as pointing

out an object to a group and seeing what others are doing, is improved (Rogers, Lim, and Hazlewood 2006). Compared to PCs, tabletops are more likely to elicit contributions from all members of a group and encourage more equal decision-making and problem-solving (Rogers et al. 2004a). Multi-touch tables have been developed so far to support language learning (Morris et al. 2005) and social skills development for autistic children (Piper et al. 2006).

Case Study: DigiTile

To show how shareable interfaces can support learning by doing, we present our work on DigiTile as a case study (c.f. Yin 2003). DigiTile is being developed and studied as part of the ShareIT Project, which aims to understand how new technologies can support co-located collaboration. The case study is presented in four sections. First, we introduce DigiTile, showing how we adapted a learning application originally developed for a desktop PC to run on a multi-touch table. Second, we describe how children collaborate using the shareable version of DigiTile. Third, we present a field study on DigiTile's learning benefits. Fourth, we demonstrate how DigiTile can be situated in a more informal learning space outside of the classroom, as part of a larger computing ecology.

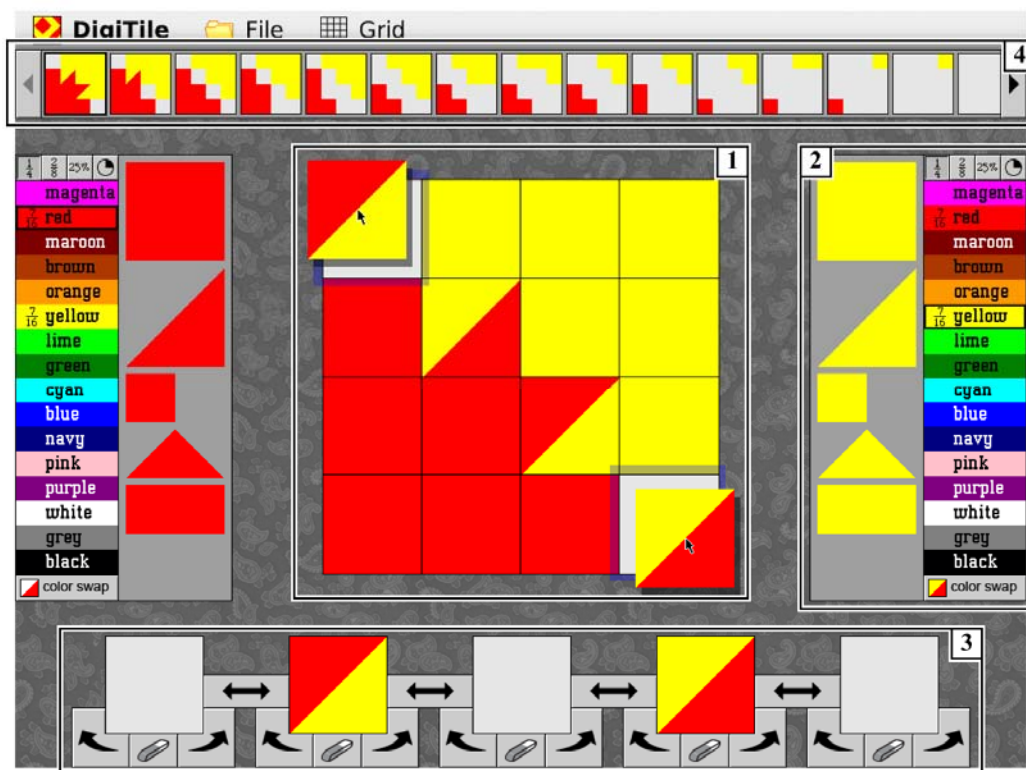
From DigiQuilt to DigiTile

DigiTile is an adaptation of DigiQuilt (Lamberty and Kolodner 2002) that runs on a DiamondTouch multi-touch table (Rick and Rogers 2008). Like DigiQuilt, DigiTile is a construction kit (Resnick, Bruckman, and Martin 1996) for learning about math and art by designing colorful mosaic tiles. In addition to being aesthetically pleasing, these tiles lend themselves to mathematical analysis. The designs embody fraction concepts and are often symmetric. For instance, the design in Figure 1 is half red and half yellow; it is also diagonally symmetric. When using DigiQuilt or DigiTile, learners are given increasingly difficult challenges to accomplish, such as creating a design that is half red or creating a design that is horizontally symmetric. DigiTile is intended to enable two co-located learners to place pieces simultaneously on the tile using touch input.

While DigiTile uses an interactive tabletop to support two concurrent users, DigiQuilt uses a conventional PC to support a single user. While DigiQuilt's interface was not intended to support collaboration, its users did frequently collaborate. Users often made comments on others' designs and occasionally sought to take over the controls to demonstrate something to a peer (Lamberty 2007). This led us to assume that it would be well-suited to being further developed as a collaborative tool. The design of DigiQuilt was also inspired by Roschelle's (1996) theory of *convergent conceptual change*—when two learners work together with a *reflective tool* (a tool that responds to user input to reflect the embedded domain concepts), they tend to converge on an understanding that is better than either would achieve independently. When learners work together on a challenge, they need to articulate their approach for solving the challenge based on their current understanding. If their strategies clash, it causes a conflict. For Piaget (1978), socio-cognitive conflict is the central mechanism for the development of individual knowledge; the conflict has a disequilibrating effect on the individual and hence he begins to test out new ideas. The reflective tool enables learners to

demonstrate or test their understanding. Thus, the conflict can be addressed and the individuals may develop deeper understanding of the subject.

Figure 1. Two users simultaneously placing pieces on a 4-by-4 tile



As they work on the challenge together, learners' conceptual understandings do not just converge with each other, but also with the domain concepts embodied in the tool (Roschelle 1996). Like DigiQuilt, DigiTile is a reflective tool, giving feedback when changes are made (e.g., the fraction updates when a new piece is placed). In addition, visual representations are particularly well-suited for discussion, so conflicts are easier to resolve (Jehng and Chan 1998). Our aim is that two learners working together with DigiTile will engage in convergent conceptual change. In this way, DigiTile has the potential to support collaborative learning.

DigiTile's interface is split into four main areas (Figure 1). The *central tile* [1] is a square grid (2-by-2, 3-by-3, 4-by-4, or 5-by-5) of snaps. Pieces can be dragged into these snaps to create a colorful tile. Users are each provided with their own *palette area* [2] on the left or right side to choose pieces of different colors and shapes. Pressing on a color button changes the color of the palette pieces. To provide feedback on fraction tasks, each color button displays the fraction of the central tile corresponding to that color. Users can drag pieces to one of the *five work snaps* [3]. There, multiple pieces can be assembled and rotated. When pieces are dragged out of a work snap, a copy is automatically created; thus, the assembly and rotation work does not have to be repeated. To clear a work snap, the user presses the eraser button below that snap. A scrollable bar contains a

graphical history [4] of how the tile was created. By clicking on a thumbnail, users can revert to an older version of the tile. Using the grid menu, users can overlay different lines on their tile; this menu also serves as a feedback mechanism, indicating whether the current design is symmetric along the respective lines.

To further utilize convergent conceptual change, DigiTile allows users to change the representation of the color fraction from reduced fraction to least-common-divisor fraction to percentage to visual pie chart, as chosen by the buttons on top of Area 2 (Figure 1). One learner can display his or her palette with percentages, while the other displays reduced fractions. This allows us to create challenges like “a tile that is $\frac{1}{2}$ red and 50% yellow.” This challenge allows the learners to discover that one-half and 50 percent are the same. Using *multiple-linked representations* to represent a mathematical concept leads to deeper understanding (Kaput 1989). This strategy would not work as well in the single-user DigiQuilt.

Adapting a single-user desktop application to a multi-touch table is not straightforward. There are many design decisions to take into consideration. These include group size, table size (Ryall et al. 2004), display orientation, and territoriality (Scott et al. 2004).

Based on convergent conceptual change, dyads seemed an ideal grouping for learners to challenge each other, while not making the collaboration too difficult. We wanted the learners to collaborate on one design, so we positioned the quilt block in the middle of the table (Figure 1); thus, learners can reach it from any location. The size of the table also needs to allow intended users to reach where they want to. In our case, the DiamondTouch table, measuring 32 inches diagonally, proved to be adequate for our intended users.

Depending on where users are sitting, the orientation of the display will affect how it is used. Unlike a desktop display, users sitting on different sides of the table will have different perspectives on a tabletop display. They could sit across from each other, around the corner, or next to each other. This makes it difficult to maintain the *desktop orientation*, where eyes up equals the top of the screen and eyes down means the bottom of the screen (Tang et al. 2006). Developing software without a dominant orientation can be tricky (Shen et al. 2004). For DigiTile, different positions would change how learners view the tile. If seated around a corner, horizontal symmetry for one partner would be vertical symmetry for the other. If seated across from each other, the tile would appear upside down. For many patterned designs, this would not be a problem; however, many DigiQuilt designs were based on real-life objects that have a preferred orientation, such as a stick figure (Lamberty 2007). In addition, while adults tend to favor working across from each other, children often prefer working next to each other (Scott, Grant, and Mandryk 2003). So, we positioned the learners next to each other to share the same orientation. This configuration (two learners next to each other) allows DigiTile to maintain a desktop orientation (Figure 1).

Territoriality refers to who “owns” what parts of the shared display and has been observed to occur in user studies of group interactions at tabletops. To encourage

individual ownership, we created a left and a right palette area, one for each user. To encourage sharing, we intentionally used an odd number of work snaps, so that one would be in the middle, implying no left or right ownership.

After some informal user testing, it became obvious that dropping a piece accidentally was fairly common in the multi-touch case. In addition, partners often disapproved of a change. For these reasons, navigating the history was more important for DigiTile than DigiQuilt. While undo and redo buttons sufficed to navigate the DigiQuilt history, we developed a graphical history for DigiTile that allows users to more easily back up to a previous design point.

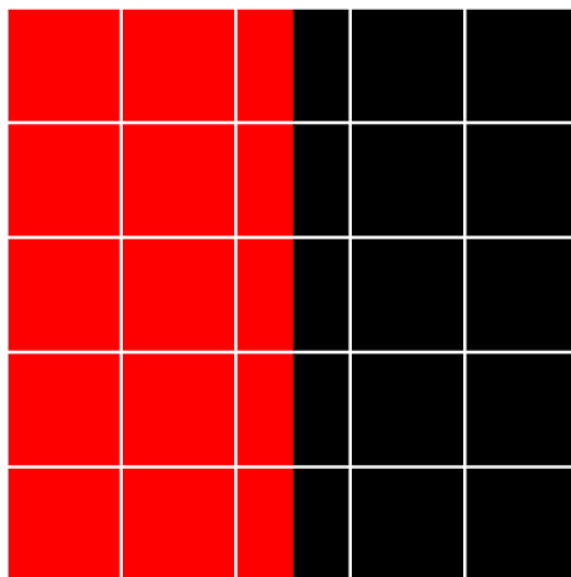
DigiTile in Action

In the previous section, we described our vision of DigiTile use, based on DigiQuilt experience and learning theory. To get a better sense of how children actually use DigiTile, we conducted a small user study with pairs of 9 and 10 year olds. This formative study enabled us to determine what level of difficulty to set for challenging design tasks that would engender collaboration. Below, we detail one exchange to illustrate DigiTile use.

To familiarize study participants with DigiTile and its touch interface, the pairs were asked to design a “good looking” tile. During this familiarization phase, the children commented on each other’s designs, sometimes leading to conflicts. It can be difficult to compromise in a way that does not leave one participant unhappy with the results. Since there was no right or wrong choice, participants often clashed about the design choices. Occasionally, we reminded them of the need to work together.

After the familiarization phase, we assigned the pairs mathematical challenges. The goal of this phase was to see how pairs would collaborate when faced with a difficult challenge—one that required significant thought and work. As observed with DigiQuilt (Lamberty 2007), when given a challenge, users shift their focus to solving the challenge, rather than creating an aesthetically interesting tile. Consequently, aesthetic-based conflicts disappear. The initial challenges proved trivial and were accomplished in less than a minute with minimum planning and negotiation between the participants. Hence, we increased the difficulty until the task became challenging. At that point, the pairs had a more difficult time forming and trialing approaches. Because both participants could interact simultaneously, it was necessary for one participant to recruit the other in trialing an approach.

Below is an excerpt from one pair using DigiTile to address the challenge of creating a tile that is half red. While this is usually an easy challenge, it proved to be quite difficult as the participants were using a 5-by-5 grid. In this case, the total number of grid squares (25) is not evenly divisible by two, so the task cannot be accomplished with whole-square pieces alone. After several failed attempts, the pair was able to create a solution (Figure 2) without the help of the researchers.

Figure 2. Solution to the half-red challenge

Researcher: [After getting a bit sidetracked, the researcher reminds them of their original mission.] *Remember that you have to get the half red.*

Girl: *Oh. I know.* [She places two black whole-square pieces on the right side.]

Boy: *Oh. I get it. I get it. I'll do the red ones. I do the red.*

Girl: *Yeah. But, we need... Wait! There—* [She gestures towards the middle of the tile.] *you see that line? Don't do any over the gray part of that line.* [Because of their previous efforts, the right side of the middle column is grey and the left side is white.] *I've just got a really good idea.* [She fills in some black on her side, while he fills in two red on his side.]

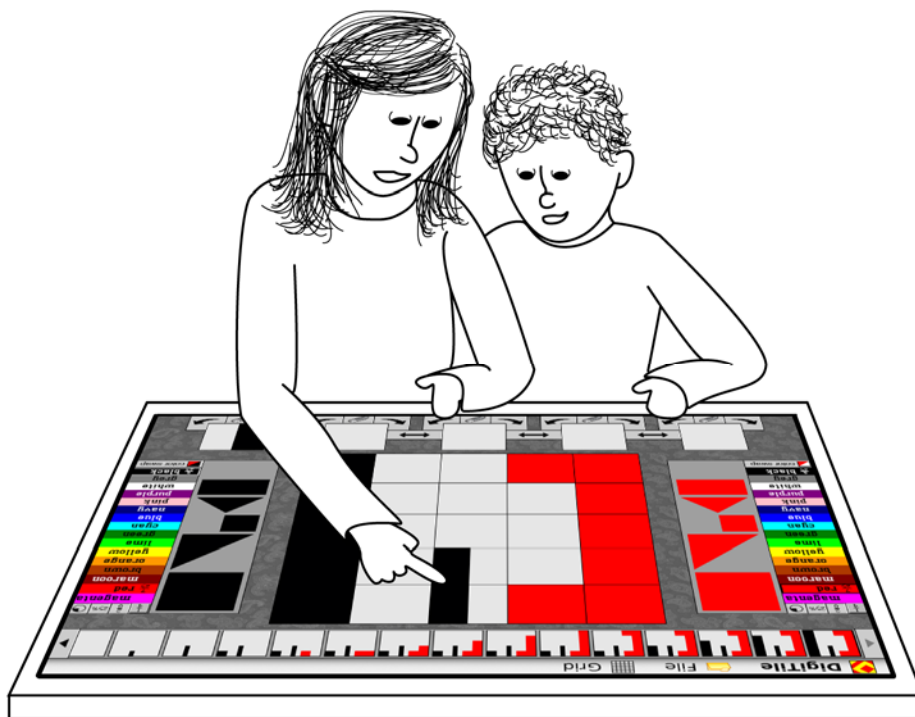
Boy: *What'd you do? Oh ya.* [He gestures to divide the middle column.] *We need a half, don't we?*

Girl: *That's what I'm going to do.* [She works to orient the half-sized-rectangular black piece to fill in her half of the middle column. Meanwhile, he fills the left two columns with whole-square red pieces. See Figure 3.] *And, then, you're going to need to use...* [She starts to point at the half-sized rectangular piece on his side. He cuts her off.]

Boy: *Yeah, I know. I am.* [He orients the half-sized red piece correctly and fills in his side of the middle column. Meanwhile, she fills the remaining empty space on her side with whole-square black pieces. They finish at roughly the same time.]

Girl: *Done.*

The pair worked together to accomplish the challenge. While the girl came up with the plan, the boy was able to follow her lead and grasp her strategy. They both placed an equal number of pieces to accomplish the task.

Figure 3. Working together with DigiTile

A Field Study

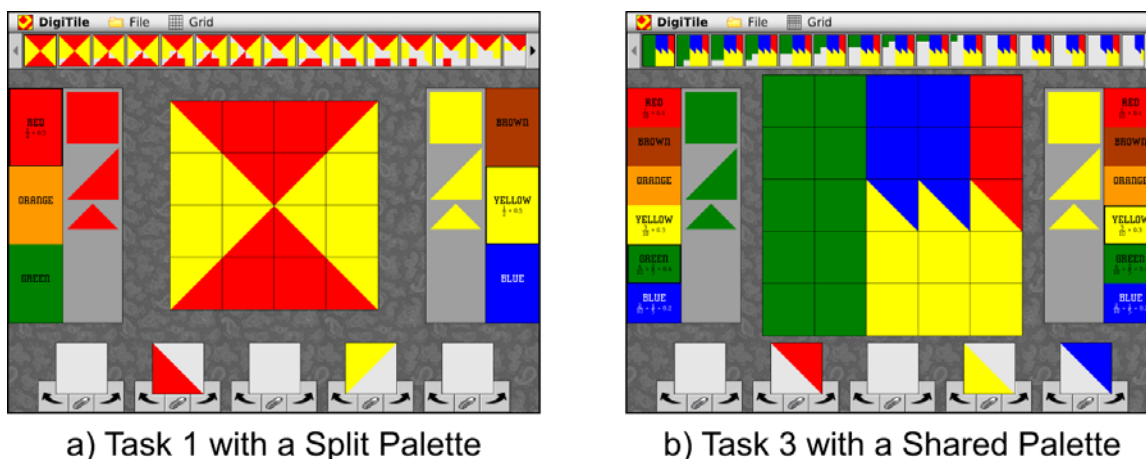
To get a better sense of DigiTile's value for promoting collaborative learning, we conducted a field study. While collaboration can promote learning, even groups with capable members often find it difficult to productively collaborate (Barron 2003). We provided tasks involving fraction understanding (rather than symmetry, shape orientation, or equivalence across representations). We simplified the interface to six colors and three shapes (Figure 4). Our hypotheses going in were that DigiTile would enable collaboration and increase understanding of fractions.

In addition, we were interested in how interface features can encourage collaboration and learning. Different access to an interface can elicit cooperation between the participants (Kerawalla et al. 2008). To investigate this possibility, we set up two conditions. In the *split palette* condition (Figure 4a), the colors were split between the two palettes. The left palette contained red, orange, and green; the right palette contained brown, yellow, and blue. In the *shared palette* condition (Figure 4b), both palettes contained all six colors. Consulting with educational experts in the area of mathematics education, we designed a sequence of three tasks that were appropriately difficult for the target group. Each task was designed to utilize the split palettes equally.

Task 1 was to create the half red, half yellow pattern shown in Figure 4a. The children were given a printout of the pattern, including grid lines, to guide their work. Task 2 was to create a 4-by-4 tile that was three-eighths orange and three-eighths brown. Participants were informed that not all of the tile had to be filled in.

Task 3 was to create a 5-by-5 tile that was one-tenth red, four-tenths green, three-tenths yellow, and two-tenths blue; an example of a successful solution is shown in Figure 4b.

Figure 4. Simplified DigiTile setup



Procedure

21 participants (9 to 11 years old) took part in the study. Children who provided a consent form (to be videotaped) were randomly allocated to an experimental group (four pairs in the shared palette condition, four pairs in the split palette condition) and paired randomly. The five students who did not provide a consent form were allocated to the control group.

All participants undertook a pre-test. Two similar fraction tests were created using a “test-based key stage two” computer program. Half the participants received version one and half received version two. The classroom teacher, who was also the school’s mathematics coordinator, helped in the formulation of the tests. The tests contained ten fraction-related questions. Participants were instructed to work in silence on the test for 25 minutes.

The following week, the DigiTile sessions were conducted in the back of the classroom during normal class time. Before starting on the first task, the researcher demonstrated how to move and rotate pieces, change their color, and use the graphical history. The participants were informed that they were going to work on three tasks and that they were permitted to talk to each other freely. Each task was read to the participants; the tasks were also provided on an instruction sheet.

This first task allowed participants to become familiar with DigiTile. At its completion, the researcher asked, “what fraction of the square is red and what fraction is yellow?” Most groups were able to come up with the correct answer on the first try; if not, the researcher helped them to realize it was one half. As a follow up, the researcher asked, “what is the percentage of that fraction?” These questions were asked to draw the participants’ attention to the fractions on the

color buttons and the different ways that they were represented (least-common-denominator fraction, reduced fraction, and decimal). The second and third tasks were given to children without any prompting or questions. The researcher neither assisted participants with the task, nor revealed solutions. Each session of three tasks lasted approximately 30 minutes; if children could not complete a task within a reasonable time frame, they were asked to move to the next task. After 30 minutes, the session was ended. At the end, participants were thanked for their efforts.

Three days after the last DigiTile session, the participants undertook a post-test. Those who previously received version one of the test completed version two, and vice versa. Two of the children who took part in a DigiTile session were absent from one of the tests; consequently, their data has been excluded from the analysis. After the post-test, the researcher demonstrated how to complete the three tasks in DigiTile.

Results

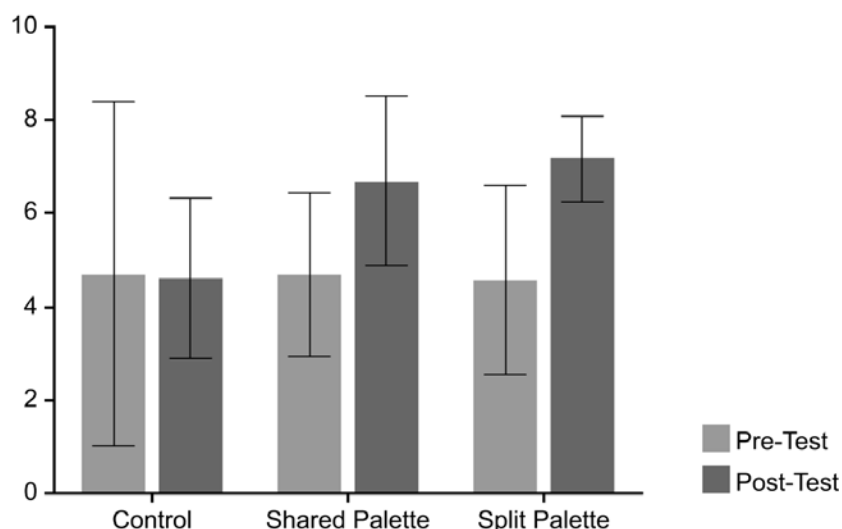
Seven of the eight groups successfully completed both Task 1 and Task 2; one group was unable to complete either task. While Task 1 was primarily designed to familiarize participants with DigiTile, it proved to be relatively challenging. In particular, rotating the triangles into the correct orientation was not trivial. It was common for participants to drag a rotated piece to a location, realize then that it did not match their intentions, and drag it back to a work area for further rotation. Task 2 was usually completed faster than Task 1. Task 3 proved to be quite difficult. Only one group finished it. One group produced a correct solution at one time, but failed to notice it was correct. The remaining six groups never completed the task, although all made significant progress. While most groups were unsuccessful in finishing the task, they did engage the mathematical concepts in their efforts.

Several common misconceptions about fractions were noticeable during the sessions. Occasionally, fraction equivalence was a problem. For example, a group would work on two-tenths, reach one-fifth, and not realize that these two fractions are equivalent. Most groups had problems realizing that higher denominators indicated a smaller fraction, which caused problems. For instance, groups would stumble onto three-sixteenths along their path to three-eighths. Because they felt the former was larger than the latter, they would start to remove pieces—an incorrect strategy. The presence of the small triangle often exacerbated this problem by creating fractions with large denominators. Several times, a group would make good progress, reach an impasse, resort to the small triangle as a possible solution, and fail to make any progress for some time.

All groups used the fraction representations displayed on the color buttons extensively for working on the second and third tasks. The prominence of the use of this feature was particularly noticeable since most had overlooked it until the researcher pointed it out after the first task. Often, one partner would add pieces, while the other kept a watch on the fraction representation.

Figure 5 shows the mean test scores for the two experimental conditions and the control group. A one-way (Group: Shared Palette vs. Split Palette vs. Control) independent ANCOVA (post-test scores) was conducted in order to discover whether DigiTile improved learning of fraction knowledge. Pre-test scores were added as the covariate. After controlling for the effect of pre-test scores, there was a significant main effect on the experimental group, $F(3, 15) = 3.45$, $p < .05$. Contrasts indicated that the experimental groups who underwent the DigiTile session had significantly higher scores on the post-test compared to the controls, $p < .05$. There was no significant difference between the post-test results of the shared and split palette groups, $p = ns$.

Figure 5. Pre- and post-test results by condition



In creating the two experimental conditions, we considered the split palette condition would improve collaboration, as participants would have to collaborate to complete the tasks. The results showed, however, that a lack of collaboration was not a problem in any of the groups. Irrespective of condition, the children worked well together. Because the second and third challenges were relatively difficult and moves often affected each other, the partners quickly figured out that they had to work together. On both the second and third task, the vast majority of the time was spent working jointly on a single color, rather than trying to work simultaneously on multiple colors.

The children also had no qualms about reaching across the table to pick up pieces from the other palette. While adults are often sensitive about their personal space, children are not. Reaching across to the other palette was also observed in the shared palette condition. In those cases, the move often modeled a behavior to the other participant (e.g., "see, you can put it here"). In one split palette group, the participants elected to switch places, so that one of them could more easily demonstrate an idea.

Discussion

This study demonstrates the benefit of collaboration for learning. Participants were able to work together (e.g., one places pieces while the other watches the fraction representation), model behavior for their partners, and articulate strategies and concepts for each other. With almost no guidance from the researcher or teacher, the children showed significant improvement in their understanding of fractions.

While we are encouraged by the results, there are several caveats to consider. First, since participation was based on returning a consent form, condition assignment was not truly random. However, since the pre-test scores for the control condition was similar to the other conditions, no overt sampling bias was obvious. Second, while the researcher did not assist on the task, her presence and the presence of the cameras was certainly an incentive for the children to stay on task and be on their best behavior.

While the results of the study were positive, this learning scenario was less than ideal. Thirty minutes is not a long time to spend on task. The three tasks certainly did not exhaust the potential of DigiTile. To truly integrate DigiTile into a class curriculum, more time and a wider variety of tasks could be useful. In order to make the experience as similar as possible across groups, the researcher kept the session on a strict task progression. Because of this, one group was unable to finish any of the tasks; consequently, their self-confidence waned (as one child concluded, “this is hard”). While that group was slower than the other groups, they were making progress. It is likely that they would have completed the first two tasks if given the full 30 minutes on just those two tasks. Ideally, the task difficulty could be adjusted to the children’s abilities, providing each group with tasks that are challenging yet ultimately doable.

While children were able to use DigiTile, there were several recurring problems with the hardware. When children bumped into the table, the DiamondTouch moved, throwing off the alignment with the projected image. This caused problems with the interface. For instance, pressing on a piece would not work as the mouse pointer would be located at a different point than the finger touch. It often took the researcher a few minutes to catch this problem and rectify it. In addition, the mats that received the signal often interfered with each other, which can happen on conductive floors. This caused problems, e.g., on a single touch, a piece in a work space would rotate by 180 degrees, rather than the usual 90, since the software received two touches (one from each pad). While a layer of non-conductive material placed underneath the pad could have solved this problem, the researcher was unaware of this.

Beyond the Tabletop

While the tabletop can be a compelling learning environment by itself, it can also fit into a larger computing ecology. To illustrate this potential, we detail our experience of using DigiTile at a large science festival aimed at families. The one-day festival featured interactive exhibits in different classrooms of the host school; hundreds of children, often accompanied by their parents, went from room to room throughout the day to interact with the various exhibits and tools. DigiTile was

networked using two computers. One ran the DigiTile application and the other was used for printing and displaying the tiles completed by the children.

When saving their designs, children named them and identified themselves as authors. The researcher at the second computer then printed a nametag featuring the design and first name of its creator for the children to wear. This served two purposes. First, it turned their virtual design into a physical artifact. The nametag allowed children to display their design prominently to their friends and family. Second, it served as an advertisement for our exhibition as children would ask previous participants where they got their nametags. The nametags were very popular, with several requests for second printings. A core emphasis of constructionism is on creating personally meaningful public artifacts. This example demonstrates how those artifacts, when used effectively, can motivate learners, embody domain concepts, and promote a culture of learning.

The other function of the second computer was to drive a large plasma screen, positioned by the door. The display program picked a design created that day at random. It ran through the history to show how the design was created. The name of the design and its creators were displayed below the tile. After arriving at the end of the history, the grid disappeared and the final design was displayed for 30 seconds. Like the nametags, the large display served as both public artifact and advertisement. Several children waited to see their designs get the big screen treatment before leaving the room. Another purpose for the big display was to emphasize the design challenges.

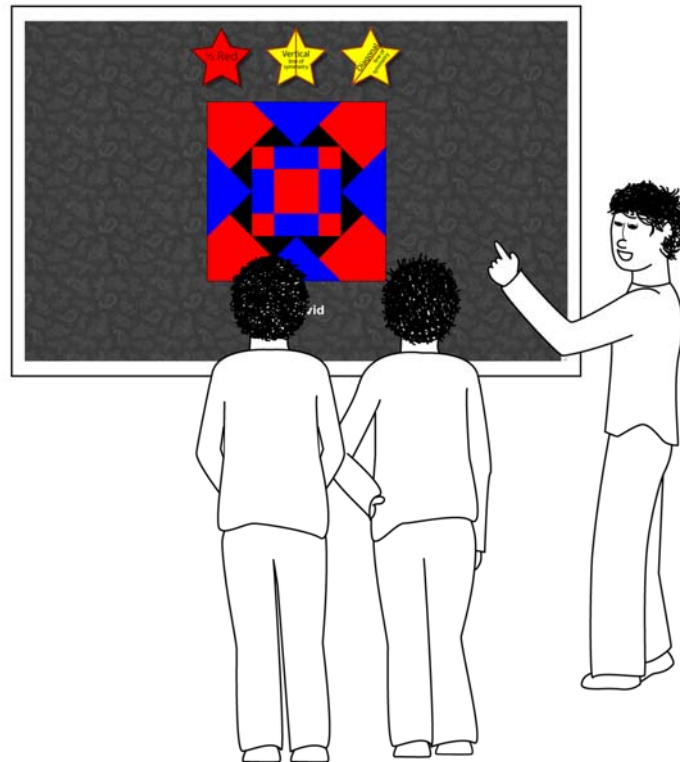
Because the children visiting the exhibition varied in age and ability, we did not directly assign any challenges. We did, however, post four challenges (half red, one-third blue, vertical line of symmetry, and diagonal line of symmetry) that participants could tackle. Some of the older participants found these interesting. When a final design was displayed on the large screen, star-shaped awards appeared above the tile for the respective challenges it met. These awards served as an incentive for new¹ participants to meet these challenges. It also became a starting point for observers to talk about the target concepts—fractions and symmetry. Towards the end of the day, a group of boys came in and spent over 30 minutes just looking at the designs that had been created during the day (Figure 6). As expected, they were excited about seeing their own designs; they also started talking about others' designs. They discussed why they liked certain designs (colors, shapes, symmetry, etc.). They also noticed the awards and started pointing out the symmetry and how the design process led to that result. It became a natural opportunity to engage the target concepts.

This example demonstrates how different computing components can work together. The display components enhanced the meaning of the created artifact. It allowed the constructed artifact to be more public (the display) and personal (the

¹Due to limited resources, we were unable to allow visitors to complete more than one design, even though many would have liked to.

name tags). It served as advertisement for others to create and became a source of discussion. In the classroom, an interactive whiteboard could allow students to present their work to each other; the teacher could then lead the kids to reflect on the target concepts, based on these displays. Outside the classroom, a public display could show the work of the students inside that classroom to others in the hallway. As our example demonstrated, this can lead to useful discussion.

Figure 6. A group discusses a design that met three design challenges



Discussion

Previously, we provided a case of shareable interfaces supporting learning by doing. We envision that this sort of constructive use will become more commonplace in education, as shareable interfaces become part of classrooms. However, significant challenges lie ahead for this vision to be realized on a large scale. In this section, we discuss the challenges and suggest ways to overcome them.

Design and Usability Challenges

Multi-touch hardware and software support is still in its early stages. The hardware is just starting to become commercially available. As was illustrated in our field study, there are still hardware obstacles and concomitant usability issues to overcome. For example, nudging the table can cause the projected image to move out of alignment. The conductive mats are sensitive to a conductive floor or non-conductive shoes (we had to ask several participants to take off their shoes for the table to properly register their touches). Other multi-touch technologies work differently and thus have different problems. Infrared light based tables, for

instance, have problems working in the presence of sunlight. Software support, too, poses a difficult interface and programming challenge. Simultaneous users and touch input are more complex than the one-user mouse input for which desktop toolkits are built. One cannot simply use existing software with the new interface.²

DigiTile is a relatively simple application, where translating the touch input into discreet mouse points works well. Other applications may benefit from more sophisticated input afforded by touch, such as pinching or putting a fist down. Developing toolkits that take advantage of touch input is still an ongoing challenge. On the positive side, there is a growing interest among commercial companies in supporting touch. For example, Apple's iPhone supports a multi-touch interface, and Microsoft has announced that the next version of Windows will support multi-touch input.

Fundamental research questions of how this kind of shareable technology can support co-located collaboration still need to be explored. Learning is a particularly challenging area, since techniques that work well with one age group may be inappropriate for others. For example, certain tabletop learning applications may not be suitable for 4 to 6 year olds because they often lack the dexterity to smoothly drag their fingers across the table without lifting them (Mansor, De Angeli, and De Bruijn 2008). Even older children, such as those in our studies, will lift their fingers while dragging digital objects, such as a DigiTile piece. These "accidental hops" can cause the objects to be unintentionally dropped in the wrong place. While these mistakes are easy to recover from they can be frustrating.

Classroom Challenges

When a new technology arrives on the scene, there is often much excitement about its ability to fundamentally change human processes and to realize a new pedagogical vision on a large scale (e.g., Postman and Weingartner 1969). Visions, however, rarely become reality. In the 1980s, Papert (1993) cast the personal computer as the device that would allow learners to take charge of their own learning. While that vision was compelling, it did not come to fruition for a number of reasons (Noss and Hoyles 1996). In the 1990s, the U.S. put a major focus on networking the classrooms and connecting it to the wealth of information and resources that is the Internet. Again, this vision has fallen short of revolutionizing learning (Bruckman 1999). More recently, there has been a big push to bring interactive whiteboards into UK schools. But, as an early progress report noted, this technology can "reinforce a transmission style of whole-class teaching in which the contents of the board multiply and go faster, whilst pupils are increasingly reduced to a largely spectator role" (Moss et al. 2007).

While most grand visions of technology-driven pedagogic change have not been realized on a large scale, there are reasons to be optimistic about shareable

² To be fair, touch input can be mapped to traditional mouse input, but then the multi-user and multi-touch aspects are lost. While it is possible to map simultaneous touch input to traditional input (Tse, Greenberg, and Shen 2006), that approach is still quite limited.

interfaces, such as multi-touch tables. First, the applications created for them are most compelling when multiple people use them together. This can encourage small-group learning in the classroom. Second, the form factors prevent them from being used like whiteboards: while it is easy for a teacher to appropriate an interactive whiteboard for a lecture, gathering the whole class around a (small) table is more awkward. Third, many shareable interfaces can run different applications to engage a variety of learning domains. Fourth, shareable interfaces build on one of the real strengths of the classroom—the potential for collaboration between peers. Hence, shareable technologies have the potential to succeed in changing the learning process to be more active in the classroom where others have failed.

If applications like DigiTile are to make it into a normal classroom, however, the classroom computing ecology needs to support it. One challenge for small group technology is that it needs to be replicated for each group. If an entire class wants to work with DigiTile at the same time, that classroom would need one multi-touch table for every two students. While this may seem prohibitively expensive now, it is becoming cheaper each year to embed computing technology in everyday things (Greenfield 2006). Another model to consider for future classroom ecology is Montessori's prepared environment, where different sections of the classroom are set up for different activities and students choose where they want to be. A single multi-touch table may be set up for DigiTile, while other engaging activities fill the rest of the classroom. The Montessori method is generally reserved for younger children, but newer technologies could make such a style of free explorations viable for learning domains generally reserved for older students (Zuckerman et al. 2005).

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